# Chapter 2

# THE DAWN OF COMPUTING

We're all quite familiar with what a computer is. You probably have one at home, and you may also have one on your desk at work, or to provide some other work function such as a cash register or for stock control. Basically, your computer at home or work is a box connected, usually by cables, but sometimes wirelessly to a mouse, keyboard, screen, and perhaps a printer and scanner. Every computer you've ever seen has probably looked much like this. However, as we will see in this and subsequent chapters, a computer need not look like this; indeed, a computer need not look like anything at all. It can even be an abstract mathematical concept with no physical reality. The computer we will look at in this chapter doesn't look like your PC or Mac; in fact it's not even electronic—it's totally mechanical.

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## THE DIFFERENCE ENGINE

In 1985 an Australian computer scientist, Dr. Alan Bromley, had been studying the original plans for a Victorian mechanical calculating machine called the "*Difference Engine No.2.*" He concluded from the plans that the Difference Engine could be built and would work. Bromley contacted Doran Swade, of London's Science Museum, and they decided to build a trial part of the Engine to test if the complete machine could be built. Assuming the trial part was a success, the 200th anniversary of its inventor's birthday on the December 26 1991 would make a fitting date to unveil a fully working Difference Engine.

I. Watson, *The Universal Machine*,
DOI 10.1007/978-3-642-28102-0_2,

The production of the trial piece pushed the technical skills of the Science Museum's engineering workshops and machinists to their limits; work proceeded slowly. Although the engineering drawings were complete, many details had been omitted such as the precise shape of teeth on the numerous cog-wheels, the materials the pieces were to be constructed from, and even the function of some elements in the design were baffling. Bromley estimated that a commercial build of the complete Engine by an engineering firm would cost around £250,000. The Science Museum was never going to fund this and neither was Margaret Thatcher's government, so commercial sponsorship was needed.

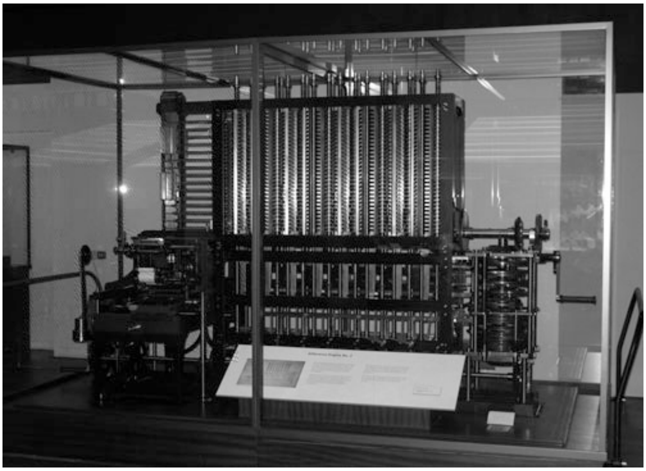
Doran Swade, the new *Curator of Computing* at the Science Museum, was planning a new computing and telecommunications gallery for the museum. A working Difference Engine, he thought would make a wonderful central exhibit, firmly positioning an Englishman as the founder of computing. *ICL* (a leading UK computer company), *Hewlett Packard, Xerox*, *Siemens* and *Unisys* came up with the necessary sponsorship and the build was on.

There were many problems because of the lack of detail in the design drawings, compounded by the obvious fact that the designer was long dead and couldn't be asked questions. For example, were the moving parts to be lubricated? If they where with what, and how? If the machine parts were lubricated, how would the lubricant be changed and cleaned, since oil and grease gathers dust that can eventually clog mechanisms. For this reason many precision instruments such as clocks and watches are sealed and designed to run dry without lubrication. The builders of the new Difference Engine had to solve these and numerous other design issues. They also found some errors in the design that had to be corrected. However, they firmly believed that had its inventor built his Engine, he would have realized his mistakes and easily corrected them. The design was inspired—an elegant thing of beauty.

Forty-six subcontracting engineering firms were contracted to manufacture 4,000 components. The Engine would sit on rails 11 feet long and be constructed in public view in the

Science Museum. The *"cast iron computer,"* as it was nicknamed by the press, started to gain media interest and its inventor's bicentennial was now only months away.

A major problem was encountered as the build neared completion and elements of the giant three-ton machine could be tested. Getting all the gears and cogs in correct alignment to start the machine was a nightmare; if the alignment was even slightly out, the machine jammed. Moreover, some cog teeth, cast in bronze, were snapping off and flying dangerously, like shrapnel, from the machine; hardly a desirable feature for a family-friendly museum exhibit.



The Difference Engine No.2 in the Science Museum, London

On the opening day of the exhibition, the Difference Engine No.2 stood proudly at the center of the display, its mahogany plinth gleaming and its oiled bronze and steel reflecting the bright lights of cameras. It's a truly wonderful creation: the ultimate *steam-punk* fantasy, a marvel of Victorian engineering and of one man's vision. A member of the build team stands ready to crank the handle to start calculating. What the watching lenses of the media don't know as the machine springs beautifully to life, is that it has been, in effect, put out of gear and into neutral. The handle turns and it seems to come to life, but the Engine is actually idling. The build team

can't risk a public failure in front of the media, so they fake it for the news cameras.

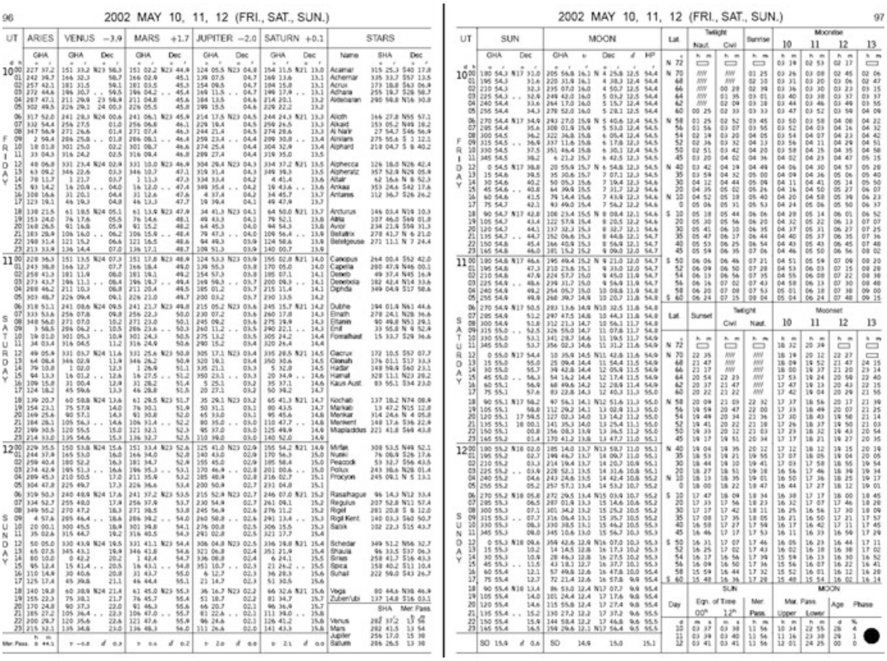
Almost a year later, by methodically ironing out all the small problems; increasing the precision of some of the components to the same exacting tolerances that obsessed its inventor, and even hand-finishing some components, just as had been done over a century before, the Difference Engine finally works. On Friday November 29 1991, 120 years after its inventor's death, the Difference Engine produced its first totally error-free, fully automatic calculation and then repeated and repeated the calculations, over and over again, without any errors. The Difference Engine works!

## THE FIRST COMPUTERS

The first computers were not mechanical; they were people. *Computers* in the nineteenth century were people who performed calculations for mathematical tables as a job, just as *typewriters* were people who typed for a living and *printers* were people who printed. Being a computer was a particularly tedious, boring and difficult job. Even up to the middle of the last century, a computer was defined in dictionaries as a person:

> ***Computer***: *"one who computes; a calculator, reckoner; specifically a person employed to make calculations in an observatory, in surveying, etc." Oxford English Dictionary, circa 1945*

These tables were vitally important; celestial and lunar tables were used by navigators to plot a ship's position on the seas. Surveyors, engineers and architects used tables in their calculations when designing buildings and bridges, whilst gunners used ordinance tables to calculate the trajectories of shells from cannon. Mistakes in these tables could therefore have serious, even deadly consequences. An example of a table from a modern celestial almanac is shown below.



A page of the 2002 Nautical Almanac published by the U.S. Naval Observatory

The people who were computers had some education, but were by no means mathletes, nor did they need to be—the calculations were typically mundane but highly repetitive. In England, computers were often retired clergymen or school teachers. In France, after the revolution, many were ex-wig makers. They had watched their wigs—and the aristocratic heads upon which they rested—being lopped of by Monsieur Guillotine's wonderful new execution machine. Now unemployed, as the number of aristocratic heads literally fell, they became computers.

For accuracy's sake, two *computers* were routinely set the task of independently calculating the same table so their results could be cross-checked for errors by a third person, called a *comparator*. Once checked, the tables would be transcribed into a single final version and then sent for typesetting and printing. After printing, the table would then be compared

again with the final transcribed table and only if no discrepancies were found, declared correct. Unfortunately, errors could be introduced at each of the four separate stages: computation, transcription, typesetting and proofing. Typesetting was a particular source of errors, as individual numbers (in mirror image) were laid out into printing blocks. When English is typeset, the typesetters, who are adept at reading in mirror image, can easily spot misspelled words or errors such as letter transposition. For example, look at this quotation from the *US Declaration of Independence*:

> *"We hold these truths to be self-evident, that all nem are created equal, that they are endowed by their Creator with certain unalienable Rights, that among these are Life, Liberty and the pursuit of Happiness."*

Spotted the error? Most of us can spot such typos easily. Now look at this sequence of numbers, which is the value of π (Pi) to 50 decimal places:

3.14159 26535 89793 23846 26433 83279 50288 41971 96399 37510

Of course you easily spotted the error and know that the correct sequence should be:

3.14159 26535 89793 23846 26433 82379 50288 41971 96399 37510

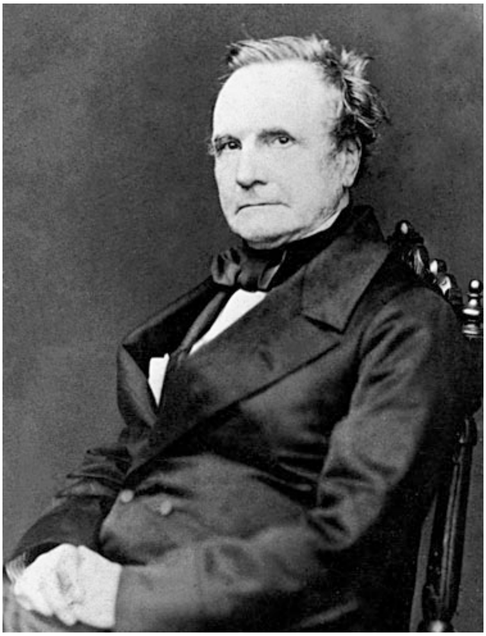
Can you even spot the difference? Now you understand the problem: manually checking page after page of numbers for errors is very, very, very difficult—in fact impossible. Thus, all of the mathematical tables in routine use had unidentified errors in them, which could lead to a bridge being incorrectly engineered or a ship's captain believing his ship was in a totally different position to its actual location.

Babbage was working with a friend in laboriously comparing the tables produced by two computers when he reportedly said:

> *"I wish to God these calculations had been executed by steam."*

By which he meant that he wished a machine existed that could produce the tables automatically. Babbage then decided he would build such a machine.

## THE GRANDFATHER OF COMPUTING



Charles Babbage in 1860

Babbage was born in 1791 in London, the son of a wealthy merchant banker. He spent most of his youth in the West Country of England, where his father's wealth enabled the young Babbage, who was a sickly child, to obtain a good education and develop a deep love of mathematics. He eventually went to Trinity College and then to Peterhouse College, Cambridge, but he was very disappointed to discover that the education there was not advanced mathematically and that he was better educated in the new continental math than his tutors. To counter the lack of advanced mathematical teaching and research at Cambridge University, he and several life-long

friends, including John Herschel (more of whom later), formed *The Analytical Society* in 1812.

Although Babbage was a brilliant mathematician, he failed to graduate with Honors because of either his stubborn independent streak or a perverse wish to destroy his career. Failing to graduate with the highest Honors would ruin the career of a young mathematician, making it impossible to get good university or government positions. The Honors exam at Cambridge was a complex ancient process, called the *Acts*, culminating in an oral, *viva voce*, exam. The candidate had to propose a thesis that would then be attacked in a formal public debate. Babbage proposed a thesis to defend that stated, "*God was a material agent.*" The moderator of the debate, one Reverend Thomas Jepherson, judged the proposition blasphemous and Babbage was promptly failed.

This result was entirely to be expected; the great majority of university academics of the time were theologians and were deeply religious. Babbage must have known beforehand that his thesis would get him shot down in flames and could not succeed. His best friend, John Herschel, advised him so, and went on himself to graduate with Honors and then get a prestigious government job. Babbage's largely self-imposed academic purgatory was the start of a life-long obsession with external recognition, and an iconoclastic war on the powerful political and scientific establishment of England. Babbage graduated in 1814 with just an *ordinary* degree.

Not content with ruining his academic reputation, Babbage then proceeded to secretly marry Georgina Whitmore, the sister of a close friend, against his father's express wishes. Babbage's father did not cut him off however, and continued to provide him an annual allowance of £300, which, though not a fortune, enabled the newlyweds to live comfortably. Still, the young Babbage had no career. He applied for several university positions, but his lack of honors and of political patronage counted against him.

Job appointments in the early nineteenth century were rarely awarded on merit. Most appointments were seen as political gifts to be bestowed upon those who lobbied the hardest or who had the most powerful friends and connections. Babbage railed

against the inequality of this system of patronage, perhaps because his father, though wealthy, was not well connected. Georgina's father died in 1816 and with her inheritance their annual income increased to a very comfortable £2,000 a year.

During this time Babbage continued with his mathematical studies and other scientific interests, and began to establish himself within the scientific circles of the time. In 1815 he gave a series of lectures on astronomy at *The Royal Institution* that were well received, and he was elected a *Fellow of the Royal Society*. In 1820 he and some friends, including his college friend Herschel, founded *The Astronomical Society* in a pub in Lincoln's Inn Fields. In 1821 Babbage and Herschel went on holiday together to the Italian Alps, and it was during this trip that the genesis of the idea of a calculating engine was born.

Babbage and Herschel were preparing a new almanac of logarithmic tables and were painstakingly cross-checking the tables produced by their two *computers*. Babbage was familiar with the whole process involved in printing the almanacs and must have known that even if he and Herschel produced perfect logarithmic tables, they could still be corrupted during the typesetting process.

Babbage set about designing a mechanical *engine* that could calculate and, most crucially, automatically print the mathematical tables. He called his invention the *Difference Engine*. Soon Babbage had made a miniature working model of his Difference Engine, and had given much thought as to how the result could be automatically printed by impressing the results into soft metal or papier-mâché that could then be used as molds for printing plates. By having a seamless process from start to finish, with no human intervention, all errors could be completely eliminated from the process.

But how can a calculating engine solve complex equations such as those used to create the results in the almanac tables? The Difference Engine was an ingenious device, being able to calculate sequence after sequence of results for a table using a well-established technique called *finite differences,* which enables complex calculations to be made just by addition without the need for any multiplication or division. The basic

technique is really quite simple but feel free to skip ahead to the next section if you're not interested in the details.

Perhaps, surprisingly to you, all actual calculations contain errors because there are limits to how much precision you can have in any real measurement. If you calculate the diameter of a circle using Pi, you will probably only use Pi to an accuracy of two or three decimal places. Even if you use Pi to 50 decimal places, that is still not as accurate as using 100 decimal places or 1,000. In 2002 a Canadian team (using a very powerful computer) calculated Pi to an accuracy of 1,241,100,000,000 decimal places, but even this is still not perfectly accurate, since Pi has an infinite number of decimal places. If an engineer measures the arch of a bridge, she can't use infinite decimal places; therefore, in real world calculations we start with approximate values that are thus inherently imprecise.

Most mathematical formulas can be approximated via polynomial series such as:

$$a_n x^n + a_{n-1} x^{n-1} + \ldots + a_1 x + a_0$$

Let's see the values for the simple polynomial: $2x + 1$.

$$\text{If } x = 1 \text{ then } 2x + 1 = 3$$

$$\text{If } x = 2 \text{ then } 2x + 1 = 5$$

And so on. We can put this into a table where ***f(x)*** is the result of the polynomial function and ***diff*** is the difference between successive results.

| ***x*** | ***f(x)*** | ***diff*** |
|---|---|---|
| 1 | 3 | |
| 2 | 5 | 2 |
| 3 | 7 | 2 |
| 4 | 9 | 2 |

The first column is the value of $x$; the second ***f(x)***, the result of calculating the result of our polynomial function (2x + 1). The last column ***diff*** is the difference between the values ***f(x)*** of the current row and ***f(x)*** of the row above. Notice that in the table above ***diff*** is always 2. In fact, for any polynomial of degree $n = 1$, the difference is always a constant.

Now let's look at a more difficult polynomial where $n = 2$, such as: $(2x + 3x) \times x$, we could construct a difference table like this:

| ***x*** | ***f(X)*** | ***diff1*** | ***diff2*** |
|---|---|---|---|
| 1 | 5 | | |
| 2 | 20 | 15 | |
| 3 | 45 | 25 | 10 |
| 4 | 80 | 35 | 10 |
| 5 | 125 | 45 | 10 |
| 6 | 180 | 55 | 10 |

In this case, the first column of differences (***diff1***) changes in value, but if we calculate the difference between their successive differences we get the values for ***diff2*** that now are all the same (10). In fact, for any polynomial of degree '*n*', the '*nth*' difference is always a constant number.

Babbage's Difference Engine works by using this principle. Once the engine is given all the values for a row, it can calculate any number of subsequent rows by simple additions. In this last example, you only need to have values of the first complete row ($x = 3$) to be able to easily generate by addition all the rest of the table. Consider $x = 4$: we know its value of *diff2* is the constant 10. We can calculate the value of its *diff1* by adding 10 to the *diff1* value of $x = 3$ to give us 35. We can calculate the value of *f(x)* for $x = 4$ by adding 35 (*diff1* for

$x = 4$) to *f(x)* of $x = 3$. 35 + 45 equals 80, thus $f(x) = 80$. Now you can calculate the values for $x = 7$.[1]

| ***x*** | ***f(X)*** | ***diff1*** | ***diff2*** |
|---|---|---|---|
| 1 | 5 | | |
| 2 | 20 | 15 | |
| 3 | 45 | 25 | 10 |
| 4 | 80 | 35 | 10 |
| 5 | 125 | 45 | 10 |
| 6 | 180 | 55 | 10 |
| 7 | ? | ? | 10 |

Okay, so we can calculate difficult polynomial equations by just using the method of difference and simple addition; but what about other mathematical equations? Here's the useful trick. Almost all regular mathematical expressions such as logarithmic and trigonometric functions can be approximated by a polynomial to a given degree of accuracy. Remember our discussion earlier, that all our measurements are approximations. So you see, we don't need to calculate our engineering or astronomical equations precisely. It's okay to approximate if we know the degree of accuracy. Moreover, if we can be certain that the approximation is completely error-free, then this is a huge advance.

Babbage knew that if a Difference Engine was provided with a complete initial row of numbers, it could calculate the value of any polynomial function that approximated other more useful functions to 20 decimal points of accuracy just by using simple additions. He imagined a machine (or *engine* as he preferred to call it) that at the simple turn of a crank handle

[1] For $x = 7$, $f(x) = 245$, $diff1 = 65$ and $diff2 = 10$

would calculate the next value for ***f(x)*** without the possibility of error. If the crank was attached to an engine such as a steam engine, and if the results could be embossed onto an engraving plate, then the entire procedure could be automated. Babbage believed that such an Engine would be of great scientific and economic advantage to Britain, since it would be the only country with truly 100% reliable scientific tables.

## BABBAGE GOES PUBLIC

In June 1822 Babbage wrote to the Astronomical Society and described his machine, claiming it produced results "*almost as rapidly as an assistant can write them down*". At this time the French, England's great rival, were producing a definitive set of logarithmic and trigonometric tables using the new Napoleonic metric system. The set of tables would run to 18 volumes and was compiled manually by a semi-industrial process involving dozens of computers and comparators, using the difference method described above. Babbage wrote an open letter to the President of *The Royal Society*, Sir Humphrey Davy, claiming that his Engine could automate the task and moreover would produce totally error free tables, unlike the French. Babbage clearly believed it to be of national importance for England to calculate faster and more accurately than the French. This would not be the last time that computers would be seen to be important to national security, as we shall see in Chapter 4.

Babbage had copies of this letter printed and sent to influential people, and eventually Sir Robert Peel, First Lord of the Treasury, took interest (yes, the same man who invented the police force). It was decided that The Royal Society should investigate Babbage's engine. A committee was formed, of which many members were Babbage's friends, and they reported in May 1823, commending the machine and concluding that Babbage, "*was highly deserving of public encouragement in the prosecution of his arduous undertaking*". However, Babbage was not without powerful enemies, including the Astronomer Royal, George Airy. He later wrote

privately to the Chancellor of the Exchequer stating that the members of the committee, "*were all private friends and admirers of Mr. Babbage*" and, "*I cannot help thinking that they were blinded by the ingenuity of their friend's invention*".

However, the Astronomical Society (remember, Babbage was one of its founders) awarded him its Gold Medal in recognition of his invention, and the government announced it would provide financial support to construct an Engine. An initial Treasury payment of £1,500 was issued. Armed with funding, Babbage set about designing a full-scale machine and toured the engineering centers of the country to learn about the latest mechanical techniques, materials and processes.

Babbage's father died in 1827, leaving Babbage a fortune estimated at £100,000. He was now free of any responsibility to earn a living, and could live as a gentleman philosopher and enjoy high society life in London. He and his wife had eight children, of whom only three lived to adulthood. Babbage lived the life of a gentleman of independent means in prosperous Portland Place, London, and dabbled in all aspects of science, eventually being elected to *The Royal Society*. By modern standards Babbage's scientific activities would seem prodigious, since he had an active interest in mathematics, engineering, cryptography, geology, and many other areas. However, this was not uncommon in Victorian England when, unlike today, an educated person was expected to be an expert in many different scientific disciplines.

His interest in cryptography and ciphers led him in 1854 to crack the *Vigenėre Cipher*, which had remained unbroken for over 300 years. However, Babbage's triumph was not publicized for nine years, until Frederich Kasiski cracked it independently. It is believed Babbage's breakthrough was kept secret for military reasons, as the British were at war with the Russians in the Crimea and the Russians were using the Vigenėre Cipher to encode their messages, which the British could now read.

Babbage also invented the *cowcatcher* for the front of railway locomotives to deflect obstacles from the front of trains and reduce the risk of derailment. Another invention of his for the railways was a *black-box* that could record the motion of a

train should there be a crash. So although the development of the Difference Engine was not Babbage's sole interest, it was however developing nicely. The main problem he faced was not of design, but rather of engineering and construction.

The basic problem was that, unlike today, there were no engineering standards. Babbage could not, for instance, order 100 brass bolts of 15/32″ gauge with matching hexagonal nuts from a catalogue. All such things were hand made by individual craftsmen and foundries as bespoke items. A bolt purchased from one manufacturer would not work with a nut purchased from another. This meant that every piece of the Difference Engine would have to be custom-made. Babbage's friend, the famous engineer Isambard Kingdom Brunel, recommended a talented draftsman and machinist, Joseph Clement, who had gained a reputation for excellent precision work, and so Babbage hired him.

Precision was key in the design and build of the Difference Engine. Babbage would tolerate no errors in the calculation, since an error early in the preparation of a difference table would then propagate through the entire calculation. Complex error-checking mechanisms were built into the design that was pushing the limits of Victorian engineering to new heights. The Engine could calculate to 50 digits of precision, but its design comprised hundreds of identical wheels and cogs.

Today a computer-controlled lathe would automatically manufacture such pieces to within a micron of accuracy. In Babbage's time, these pieces had to be individually cast or milled and then finished by hand to ensure, for instance, that two inter-meshing cogwheels had a precise accurate fit. This was a laborious and expensive process. The Engine had approximately 25,000 individual parts, was eight feet high, seven feet long and three feet deep! Fifteen tons of handcrafted high precision components; a mechanical build of this complexity had never been attempted before.

1827 was a momentous year in Babbage's life. The death of his father affected him deeply, even though their relationship had been a stormy one. Later in the year his young son, also called Charles, died and then in October his wife, Georgina,

died in childbirth along with his newborn son. Babbage was devastated, and near physical and mental breakdown. On the advice of friends, he left England for a continental tour.

He obtained leave from the government to suspend work on the Engine, and spent over a year touring Europe. Although he had received £1,500 from the Treasury the design and build, he estimated, had already cost him over £3,000 (and this would be discounting the estimated £3,000 he had spent developing the initial design). With hindsight, perhaps, requesting complete reimbursement of expenses for the project whilst on an extended European holiday, with the project on hold, was not the most politic idea.

Five or six years after the project had started, and with nothing to show for their money, people started questioning whether further huge sums should be committed. Letters were written to the *Times* newspaper, and Babbage's detractors even insinuated that monies had been misappropriated.

On a positive note, Babbage was elected to the *Lucasian Chair of Mathematics* at Cambridge University. This is the position that Sir Isaac Newton had held, and which Professor Steven Hawking held until recently. It seems strange to us now that Babbage never felt he achieved the recognition and distinctions that he deserved, when he would be in the same company as Newton. In fact, Babbage actually considered declining the appointment, which only paid £100 per annum, but appeared to have no required duties. He didn't even have to live in Cambridge or give any lectures. However, on the advice of friends, he accepted and held the post for a decade. Afterwards he commented bitterly that it was, "*the only honor I ever received in my own country.*"

Babbage was, understandably, deeply upset by allegations of financial impropriety and wrote to the Prime Minister, the Duke of Wellington, who passed the buck to the Royal Society, which, you guessed it, appointed a committee, chaired by Babbage's old friend Herschel, to investigate. Not surprisingly the committee's report totally vindicated Babbage and a further £1,500 was obtained from the Treasury.

The financial insecurity of the project had caused problems with Babbage's relations with Clement; by all accounts a

difficult man to deal with at the best of times. The relationship between the two men had developed poorly and it had become difficult to tell what was Babbage's original design and what was Clement's development. This was particularly true for the machine tools that Clement had developed to fabricate the components.

Babbage now tried to formalize their relationship and claimed all intellectual property in the drawings and the tools, whereas Clement, as was customary at the time, claimed ownership of his tools. He also claimed that he was still owed £2,000 despite having already been paid £3,000. Clement ceased work in May 1829 and the pair were forced into arbitration. Clement was paid in full and work resumed, but their relationship had been badly damaged.

Babbage now estimated that it would take three years to complete the build, and once again he applied to the Treasury for more funds. Once again it was referred to the Royal Society, which endorsed the proposal. Because of the size of the Difference Engine, a new building was constructed where Clement and his family could live on-site. Clement was also instructed to build a small section of the Engine so that Babbage could demonstrate its function, and perhaps reassure the Treasury that it would work. In 1832 the demonstration section, about two feet square, was installed in Babbage's house.

Clement had never been happy with the move to new premises, since it meant he had to close down his own workshop, and he had claimed £600 in compensation. After a prolonged and bitter dispute, Clement's claim was rejected and in March 1833 he downed tools again, fired all his employees and walked off the project. A complex wrangle then ensued over the drawings of the Engine, the machine tools and components, involving Babbage, Clement and the Treasury. So far the project had cost almost £17,000—a huge sum of money in the day. By comparison, less money had been offered as the prize for the solution to estimating longitude accurately on ships.

It took a whole year for the dispute with Clement to be resolved and all drawings, tools and parts to be returned to Babbage. During this time Babbage was demonstrating the

small working section of the Engine at social functions in his house, to the wonder of guests. This "*finished portion of the unfinished engine*" was the only piece to be completed in Babbage's lifetime.

## THE ANALYTICAL ENGINE

During the long delays in construction of the Difference Engine, Babbage had started to revisit his design, and perhaps playing with the working section had made him rethink his original ideas. The notion of calculating based on differences was elegant and efficient, but limiting. Babbage was starting to envisage a general-purpose calculating engine that could perform any calculation—a more *universal* engine. In particular he was starting to think about how the product from one calculation could be fed as an argument into another subsequent calculation. In this way complex computations could be built up from simpler components.

He tinkered with the working section of the Difference Engine to allow a digit from one column to be fed automatically to the input wheels of another. With a leap of insight, he redesigned the linear array of calculating columns in the Difference Engine into a circular layout where the last column could feed its results back to the first. Babbage referred to this as, "*the Engine eating its own tail.*"

Babbage wrote: "*The whole of arithmetic now appeared within the grasp of mechanism*. *A vague glimpse even of an Analytical Engine at length opened out, and I pursued with enthusiasm the shadowy vision*." From 1834 to 1836 Babbage invented automated mechanisms for multiplication and an ingenious, though complicated method for mechanical long division. Babbage became almost totally fixated on the design of the Analytical Engine and employed new staff to help him produce the technical drawings. Work on the Difference Engine had now completely stopped.

Babbage was highly knowledgeable in aspects of advanced machinery, and in particular was inspired by complex textile manufacturing equipment; state-of-the-art machines of their time. Some of the terms used to describe the Analytical

Engine are derived from textile manufacturing. As a computer science professor, I have often told students that the Analytical Engine has the same architecture as a modern computer.

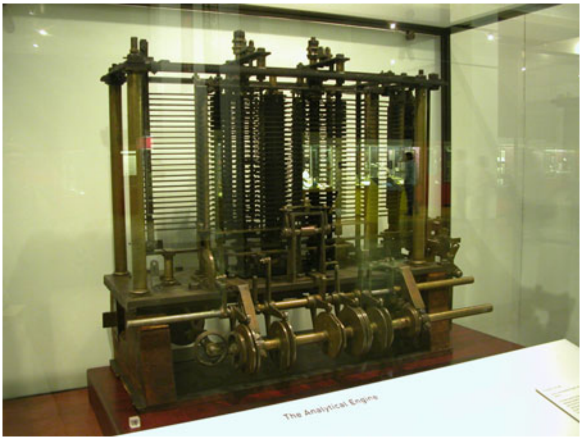
The Analytical Engine is a computer made of component parts. *The Store* contains numbers to be processed or operated on—we would now call this memory. *The Mill* processes the numbers from the store—we would call this the central processing unit (CPU). In the Analytical Engine there is both a logical and physical separation between memory and CPU. Babbage also envisaged input and output devices that were remarkable prescient: punch card readers to provide calculating instructions to the Mill (i.e., programs to the CPU) and numbers to the Store (data to the memory) and output to printers using carbon paper, or to punch cards. The use of punch cards was directly borrowed from weaving machines, like the Jacquard Loom that used these cards to input the complex patterns for lacework.

Punch cards for a Jacquard Loom

Although punch cards are no longer used by computers they are still used by some modern knitting machines.

So during a couple of years in the mid-1830s, Babbage had designed a machine that could automatically add, subtract, multiply and divide numbers 50 digits long. These simple arithmetic operations could be combined into complex calculations that could include iterations or loops as well as conditional branching (if ... then statements). The machine could read its instructions in from punched cards and output its results to punch cards that could be stored and used later, or it could directly print its results in duplicate. The Difference Engine could perform one calculation over and over reliably, but the Analytical Engine could in theory perform any calculation that could be programmed into it. The Difference Engine was a calculator; the Analytical Engine was a computer.

The Analytical Engine would have been a colossus! The Mill was 15 feet tall and six feet in diameter, whilst the size of the Store depended on its capacity (just like modern memory). To store 150 numbers would require about 20 feet of Store. Babbage envisaged a Store for a 1,000 numbers over 100 feet long. The Analytical Engine was never built, but it would have been one of the engineering marvels of its time; right up there with Isambard Kingdom Brunel's Great Western Railway, the Clifton suspension bridge and the Great Eastern steamship.




Trial model of a part of the Analytical Engine, built by Babbage

Somewhat understandably, Babbage had now lost interest in the Difference Engine, but the stalled project was a constant reminder and given the huge sums of public money sunk into it, he was worried as to what his duty to finish it might be. In December 1834 he wrote to the Duke of Wellington, now Foreign Secretary, stating that he had developed "*a totally new engine possessing much more extensive powers*". He latter clarifies this letter and states that, "*it would be more economical to construct an engine on the new principles than to finish the one already partly executed*". Effectively he is saying that the Difference Engine was obsolete. The government acted rather calmly to this revelation and there were no immediate repercussions. This of course may have been a simple oversight, since there were four chaotic changes of government within months of each other at this time.

You may think that since Babbage had little interest in completing the Difference Engine, which he now thought obsolete, that he'd be happy to let sleeping dogs lie, and that if the Government in its confusion had taken its eye off the ball, then he'd be well advised to let the aborted project quietly drift into history. But no, in 1842 Babbage started writing to the new Prime Minister, Robert Peel. The Prime Minister had some rather pressing issues on his agenda, like rioting and starvation in Ireland, and an industrial depression, and he eventually passed on the issue of what to do about the Difference Engine project to the Chancellor. Rather than consult with the Royal Society and Babbage's old friend Herschel as before, the Chancellor asked the Astronomer Royal, George Airy, to advise. Airy had never seen the utility of the Difference Engine. In particular he did not see the need to automatically generate navigational tables when they had been economically produced for years by hand. Airy wrote:

> *"The necessity for such new tables does not occur, as I really believe, once in fifty years. I can therefore state without the least hesitation that I believe the machine [the Difference Engine] to be useless, and that the sooner it is abandoned the better it will be for all parties."*

> *"On Sept. 15th Mr. Gouldburn, Chancellor of the Exchequer, asked my opinion on the utility of Babbage's calculating machine, and the propriety of expending further sums of money on it. I replied, entering fully into the matter, and giving my opinion that it was worthless."*

This was damning stuff, since it went to the heart of the need for "*the machine*," not the likelihood of successfully building it. Airy was arguing that it didn't matter if the Difference Engine worked or not; it just wasn't needed.

Gouldburn wasted no time, and wrote to Babbage saying that the Government would spend no more money on the Engine, and that it would have no claim on it whatsoever. However, Babbage was free to do what ever he wished with the partially completed Engine. Now we can understand that Babbage would be upset by the official axing, after 20 years, of his life's work. We'd also expect him to be angered by Airy's dismissal of the Engine. However, it seems that Babbage completely lost the plot, even though he didn't really want to continue the development of the Difference Engine anyway.

He demanded a meeting with the Prime Minister, although he'd been advised by a friend that he should not anger Peel because he was exhausted with the demands of office during very turbulent times. Babbage went into the meeting with all guns blazing, demanding reimbursement for all the time he'd lavished on the project to date, and wanting payment in advance for the completion of the Engine and the right to own the copyright on all tables produced by it in the future. He also demanded a civil honor (such as a knighthood) and perhaps a state pension to prove that he had acted honorably throughout the project.

Peel, not in a good mood anyway, was apparently very angry. Even Babbage says so, and he was kicked out of Downing Street. The Difference Engine project was now quite dead.

## THE ENCHANTRESS OF NUMBERS

Around this time, a woman enters our story. Ada, the Countess of Lovelace, sounds like a character from a bodice-ripping novella, but she was actually the daughter of Lord George Byron, the celebrated romantic poet. She was for her time rather an unusual young woman and perhaps, as a consequence, a lot of nonsense has been written about her. So let's first kill a couple of the untruths.

Ada was not the world's first computer programmer, even though the programming language Ada is named after her. She was not Babbage's patron; he was after all a wealthy man in his own right and the government had been funding the development of the Difference Engine anyway. However, she was a remarkable woman for her time, with a keen interest in science and mathematics in particular.

Remember that in times past, women's minds were held inferior to men's and it was widely thought they were only good for looking after a home, raising children and perhaps embroidery and pretty piano playing. As Jane Austen observed, "*A woman, especially, if she have the misfortune of knowing anything, should conceal it as well as she can.*" However, Ada believed, "*The more I study, the more remarkable do I feel my genius for it to be.*" Ada's mother, Lady Byron, had been mathematically educated. Byron referred to her as his "*Princess of Parallelogram*s" and encouraged his daughter to be similarly educated.

Ada the Countess of Lovelace

Ada moved in the same elevated social circle as Babbage, being married to the Earl of Lovelace, and she became fascinated with the Difference Engine and the potential of the Analytical Engine after meeting him at a party and later seeing a demonstration of his "*Thinking Machine.*" She understood what a breakthrough to science and engineering a reliable computer would be.

In 1840, Babbage had visited Italy and given some lectures in Turin that had been very well received. An Italian engineer, Luigi Menabrea, had subsequently published a description of the Analytical Engine in Italian. Ada translated this paper into English, and at Babbage's request added comments of her own. In collaboration with Babbage she worked vigorously on the project, signing herself in correspondence as "*Babbage's*

*Fairy.*" However, once again Babbage was to fall out with a collaborator.

Ada was keen to gloss over the troubles that Babbage had with the building of the Engine and with the government, whereas Babbage saw publication as an opportunity to vindicate his position and his reputation. In the end their writings were published separately; hers in *Scientific Memoirs* and his in *The Philosophical Magazine.* Ada*'s Sketch of the Analytical Engine* was very well received, and her lengthy additional notes to Menabrea's original description gave her the freedom to muse on the Engine's more philosophical aspects. She comments that:

> *"The Analytical Engine weaves algebraic patterns just as the Jacquard loom weaves flowers and leaves... Supposing for instance, that the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptation, the Engine might compose elaborate and scientific pieces of music of any degree of complexity or extent."*

Ada was the first person to hypothesize that a machine, by manipulating symbols, could perform a task like composing music. In essence a machine, like the Analytical Engine, could perform any task that could be expressed in symbols. It would be a universal machine.

> *"Many persons...imagine that because the business of the Engine is to give its results in numerical notation the nature of its processes must consequentially be arithmetical and numerical, rather than algebraical and analytical. This is an error. The engine can arrange and combine its numerical quantities exactly as if they were letters or any other general symbols; and in fact it might bring out its results in algebraic notation, were provisions made accordingly."*

In her extensive notes to her paper she describes an algorithm for the Analytical Engine to compute Bernoulli numbers. It is considered the first algorithm written for implementation

on a computer, but it is far from being a "*program*," more like programmer's pseudo code. It is this that has led people to claim her as the "*first computer programmer.*"

Just as now, they thought about using the machine to play games. Babbage wrote: "*every game is susceptible of being played by an automaton.*" He even invented a machine for playing tic-tac-toe and toyed briefly with the idea of starting an arcade games business. Nobody would realize that a computer was a symbol manipulating machine, and could solve any task that could be represented by symbols, until Alan Turing almost a century later had the same remarkable insight.

As an aside, it is also worth noting that it is certain that Ada had read Mary Shelly's Gothic story *Frankenstein*, which was extremely popular. Mary Shelly was the poet Percy Shelly's wife, and Shelly was the best friend of Ada's father, the "*mad and bad*" Lord Bryon. In Frankenstein, medical science and electricity is used to create a conscious being, the monster, who eventually turns on his creator because he can't find love. Ada and Babbage were thinking about using mathematics and engineering to create a machine intelligence. The *Frankenstein myth* is at the heart of much science-fiction, most notably in *2001 A Space Odyssey*, *Blade Runner* and the *Terminator* series. The Frankenstein myth and computers were thus intertwined at birth, and we will probably always wonder if our creations may turn on us in the future.

Tragically, in 1852, Ada died of cancer at the age of just 36 and is buried next to her famous poet father. Although she was a very remarkable woman for her time, writing the most well-known and influential article describing the Analytical Engine, historians are wrong to believe that she helped Babbage in any way with its design, and they stretch the truth to say she wrote computer programs for the Engine.[2]

[2] Since 1998, the British Computer Society has awarded a medal in her name and Ada Lovelace Day is an organization whose goal is to "*raise the profile of women in science, technology, engineering and maths*" http://findingada.com/

## THE DIFFERENCE ENGINE NO.2

Babbage never built the Analytical Engine, but it seems that the design process had inspired him, and between 1846 and 1849 he started work on a new design for a *Difference Engine No.2*. This used the same mathematical principle as the original Difference Engine, but was an improved and much simpler design, using just one-third the number of components to perform the same calculations. Even so, it was still a massive construction; 11 feet long and seven feet high, with 4,000 parts.

We don't know why Babbage returned to the Difference Engine. Was it because he now saw he could improve its design, or was it because he still wanted to satisfy his obligation to the government, which had funded its development? In 1852 he offered the new plans to the government, which were promptly rebuffed and once again Babbage went off in a huff. Perhaps because No.2 was never built and the plans were therefore not used, he left a complete set of 24 detailed engineering drawings that eventually found a safe home in the Science Museum in London.

Babbage's relationship with the establishment suffered another blow. The Great Exhibition of 1851, held in the specially designed Crystal Palace, was the largest exhibition of science, engineering and manufacturing technology ever staged. It was intended to show the world the prowess, might and genius of the Victorian industrial revolution. Six million people visited during its five months. As an eminent Fellow of the Royal Society and a celebrated mathematician, inventor and engineer, Babbage had been expecting to be heavily involved with its organization, perhaps as a Commissioner for Prince Albert. But Babbage was snubbed, probably because he had now earned himself a reputation for being impossible to work with. In response, Babbage dipped his pen in poisoned ink and wrote *The Exposition of 1851: Views of the Industry, the Science and the Government of England*. This bitter piece of work, and in particular a lengthy attack on his arch nemesis the Astronomer Royal George Airy, did Babbage no favors in high places.

## A SWEDISH DOPPELGÄNGER

Meanwhile, in parallel to our story a Swedish publisher, journalist and printer, George Scheutz, had been devouring all he could find in print about Babbage's Engines. Despite the fact that the published articles didn't describe the design in detail, George and his son, Edward, set about designing and building their own Difference Engine. Theirs was much simpler than Babbage's; it lacked the complex error prevention mechanisms and was even partly made out of wood. By 1843 the Scheutzes had a working prototype, and in 1851 they persuaded the King of Sweden to invest the modest sum of £270 for further development. The contrast between the Swedish and English experience could not be more pronounced. By the end of 1853, an engine that could calculate four orders of difference to 17 decimal places and automatically print tabulated results was completed, and in 1854 they brought it to the Royal Society in England to display and possibly sell.

Not surprisingly, the Scheutzes were worried that Babbage might be angry that they had copied his ideas; but quite to the contrary he was fascinated and flattered, and welcomed them graciously. It seems that although Babbage was always concerned about getting the recognition he deserved for his inventions, he was a committed member of what we'd now call the *open source* movement—he firmly believed that scientific discovery should be used for the benefit of all mankind and not for personal financial gain. Of course that's an easy line to take if you're already hugely wealthy. Babbage wrote:

> *"They may lock up in their own bosoms the mysteries they have penetrated.... whilst they reap in pecuniary profit the legitimate reward of their exertions. It is open to them, on the other hand, to disclose the secret they have torn from nature, and by allowing mankind to participate with them to claim at once that splendid reputation which is rarely refused to the inventors of valuable discoveries in the arts of life. The two courses are rarely compatible."*

This comment was instigated by his discovery that a friend, William Hyde Wollaston, had kept secret a process to produce malleable platinum for 24 years thereby earning a fortune. As we'll see later, Babbage would have a lot in common with many modern computer scientists.

The Astronomer Royal, though, was not so welcoming to the Scheutz's Engine; once again he put forward his view that despite the accuracy of the machine and the fact that Scheutz's Engine could be produced inexpensively, nonetheless there was no need for it, *"as I believe, the demand for such machines has arisen on the side, not of computers, but of mechanists"*. Airy believed that since usable mathematical and astronomical tables already existed and rarely needed to be recalculated, there was no economic need for these machines.

The Scheutz Engine went on from London to the Great Exposition of Paris in 1855, and then returned to London where it was used to produce a 50 page promotional book: *Specimen Tables Calculated and Stereomoulded by the Swedish Calculating Machine*. This was to be the only time the Engine was to be used. Eventually it was sold for £1,000 to the Dudley Observatory in Albany, New York, where it was never used, and now it rests in the Smithsonian in Washington DC.

However, the tale of the Swedish copy of the Difference Engine is not quite finished. During the time the Engine was being shown at the Royal Society, William Farr, the Chief Statistician at *The General Register Office*, became interested in the Engine. Responsible for calculating tables of life expectancy, life insurance and premium tables from census data, he saw the need for automation, particularly since unlike astronomical tables, these had to be regularly recalculated after every census. In 1857, Scheutz and Farr petitioned the Chancellor to provide money to fund a second Scheutz Engine that could be used by three government agencies: *The Royal Observatory*, *The Nautical Almanac Office,* and *The General Register Office*. Once again Airy was asked for his opinion and he concluded that the Engine, whilst of no use to him or the Nautical Almanac Office, would be of benefit to the General Register. Airy's change of mind rather disproves the view that

he just didn't like Babbage and his machines. Once he saw the economic need for the regular and reliable production of actuarial tables, he became a convert to mechanical computing.

The funds were duly granted and a second Engine was built by Donkin & Co. in 1859. The Engine was then used to produce the 1864 edition of the *English Life Table*. However, since Scheutz's design had none of the complex error prevention mechanisms of Babbage's Difference Engine, the machine had to be constantly tended and watched, and its results constantly checked. Babbage's obsession with perfection had proved to be a necessity, not a luxury—an automatic computer was only of use if it was guaranteed 100% error-free. In the end, of the 600 pages of tables, just 28 were produced solely by the Engine and a further 216 partially. George Scheutz died a bankrupt in 1873, and the Scheutz-Donkin Engine can now be seen in the Science Museum in London alongside Babbage's Difference Engine.

## BABBAGE'S LEGACY

Ten years after he'd stopped work on the Analytical Engine, Babbage returned to it, dusting off the design and improving sections of it. By 1859, Babbage estimated he could complete the project in about two years, and began ordering components. Four years later it was still unfinished, and by the late 1860s he was still tinkering with the design.

Babbage died on Wednesday October 18 1871 and is buried in Kensal Green cemetery, London. He had published 86 scientific papers, numerous miscellaneous articles and six books, risen to hold the Lucasian Professorship of Mathematics at the University of Cambridge, and dreamed up numerous inventions in areas as diverse as geology, ophthalmics, railways, lighthouses, submarines, electricity, cryptography and even theatre lighting. Even by the industrious standards of his day he had achieved a great deal, yet his life's great work remained unfinished. Neither the Difference Engine nor the Analytical Engine were built during his lifetime.

If you are ever in London, take the time to visit the Science Museum in the South Kensington museum district. In addition to lots of other interesting displays you can see the working replica of the Difference Engine No.2, along with the working part of the original Difference Engine that Babbage had built to demonstrate his ideas. There is also a model of the Analytical Engine, some of Babbage's notebooks and rather oddly half of his brain, pickled in a jar! I visited recently whilst researching this book and I'm now left wondering why they have half of Babbage's brain on display and where's the other half?

After Babbage's death and the failure of the Scheutz Engine, the quest for automated calculating machines died (at least in England) for almost 100 years. Many people speculated that The Difference and Analytical Engines were never built because they were technically impossible. Babbage had been an amateur dreamer, not a serious engineer; a gentleman dabbler, not a professional career scientist.

So what then was Babbage's legacy and what influence did he have on the development of the modern computer? After all he is often referred to as the "*Grandfather of Computing.*" Well, there is some disagreement on this. Many writers cite the architecture of the Analytical Engine, with its separate store for numbers and its processing mill that can be programmed via punch cards, as the direct ancestor of the modern computer. Whereas, in reality the developers of the first electronic computers did not claim to have been influenced by Babbage at all. Of these, only Howard Aitken, who developed the electro-mechanical Harvard Mark 1 at IBM in 1943, claims any influence from Babbage.

Allan Bromley, a historian and computer scientist, states, "*Babbage had effectively no influence on the design of the modern digital computer*". This echoes the verdict of Maurice Wilkes, a distinguished British pioneer of computing, who wrote in 1971 to mark the centenary of Babbage's death, "*[Babbage] however brilliant and original, was without influence on the modern development of computing*". Indeed, Wilkes goes further, arguing that Babbage's costly and very public failure caused the British to shun anything to do with mechanical calculation for almost a century. Perhaps it was

this, as we shall see, that caused the Americans to gain a lead in mechanized numerical and information processing. This view was supported by a colleague of Wilkes', L.J. Comrie, who was superintendent of the Nautical Almanac from 1930 to 1936. He used an American Burroughs machine for generating and detecting errors in navigational tables. Wilkes reports Comrie claiming: "*this dark age in computing machinery, that lasted one hundred years, was due to the colossal failure of Charles Babbage.*"

The fact that Babbage's Analytical Engine and the modern digital computer share the same architecture should perhaps then be put down as an example of *parallel evolution*, a phenomena well understood in the biological sciences. For example, it is no accident that sharks and dolphins look very similar. They share the same environment and are under similar evolutionary pressures. However, they evolved separately into the similar forms we see today. Thus, the developers of the modern computer had to solve similar problems to Babbage's, albeit with electronics rather than mechanics. As a consequence, they end up with a similar architecture. It is now only with hindsight that we can look to Babbage and think, "*he thought of all this first*;" input and output devices, a programmable central processing unit and separate memory storage for data, and most importantly, a machine that could be programmed to perform any task. A universal machine![3]

[3] As this book was being completed "*Plan28*" was announced to build a working Analytical Engine just as has been done for the Difference Engine No.2. This project is a little harder though as Babbage didn't complete the design of the Analytical Engine and complete engineering drawings do not exist. The team members must first complete the design to Babbage's intentions and then build a working "*steam powered-PC.*" More information here: http://plan28.org/